Electrical Supporting Information:

Large-scale climate variability footprint in water levels of alluvial aquifers across Iran

by

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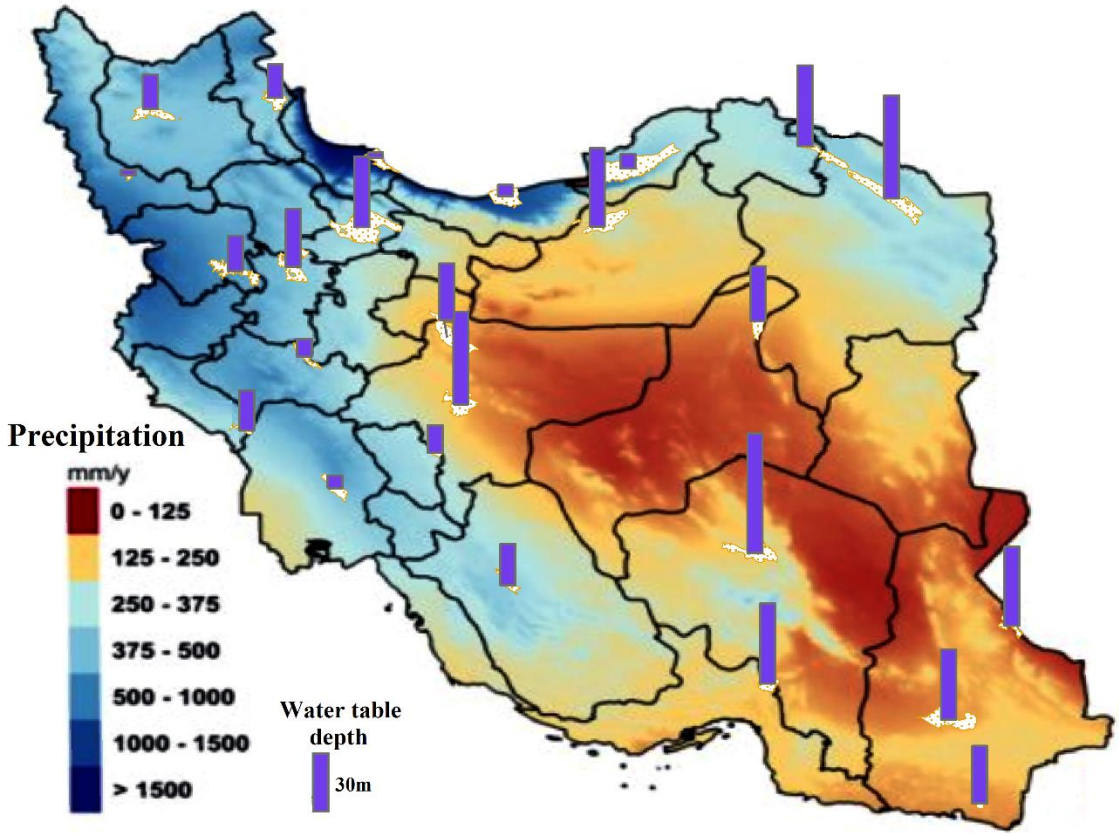


Fig. S1. The selected aquifers and their water table depth overlaid on the mean annual precipitation map over Iran (Mesgaran et al., 2016, Evaluation of land and precipitation for agriculture in Iran. Stanford Iran 2040 Project, (2)).

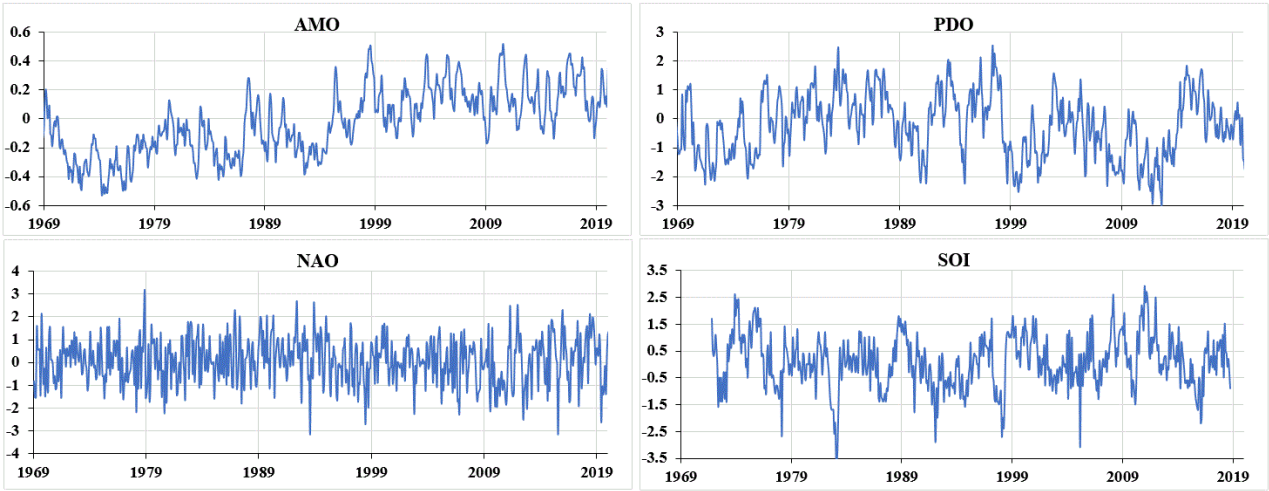


Fig. S2. The monthly time series for AMO, PDO, NAO, and SOI from 1969 to 2020.

WTC analyses in more details:

For group G1 (aquifers 1a, 1b, and 1c), both the PDO and SOI show the highest and roughly the same coherence pattern with groundwater compared to AMO and NAO (Fig. S. The WTCs demonstrate that PDO and SOI's strong (>0.95 confidence level) coherence patterns are more concentrated in 8-16-yr periods across the whole transect (e.g.,1971 to 2018.7 in aquifer 1a). AMO's strong coherence patterns are also concentrated in both the annual and >-8-yr periodicities, particularly in aquifer 1c. Regarding the annual periodicity, the highest coherence patterns are first related to AMO and then to PDO and NAO. SOI shows the lowest coherence with groundwater in G1 across the annual periodicities. Overall, there are four scales in which significant coherence patterns exist between groundwater and climate indices: annual (more controls by AMO and PDO), interannual of 4-6-yr (highly control by SOI and PDO), interdecadal signals of 8-12 (highly affected by SOI and PDO) and >15 (PDO and AMO).

Although in group G2 (aquifer 2), the length of the data is not that enough to show the ~7-yr periods, the WTC results show that the annual signals are highly correlated to AMO across the whole transect (1996-2019) while the interannual signals (3-7-yr) are more controlled by PDO and SOI. However, both the PDO and NAO also have some significant patterns at annual periods, particularly during 1998-2000, 2006-07, and 2010-2019 for PDO and 1998-2004 and 2014-2015 for NAO. The phase relationships (black arrows on the WTCS graphs) indicate that AMO has an in-phase relationship with groundwater in annual periods while NAO, PDO, and SOI is relatively anti-phase covariation.

In group G3 (aquifer 3), PDO has moderate to strong coherence patterns with the aquifer across periods of (1) 2-7-yr for the whole transect (1987-2019), >8-yr from 1987-2005, and 1-yr over the whole transect except for 2004 and 2007-2010. Although AMO's coherence pattern in 1-yr periods is highly significant, particularly since 2002, it also has some moderate to strong coherence pattern around 4-6-yr and >-8yr. NAO shows 4 moderates to significant coherence patterns with groundwater at four periods: 1-, 2-3-, 4-6, and >10-yr. SOI's significant pattern has occurred across 5-7-yr periods, although it has some other coherence patterns in 1-, 2-3, and >10-yr periods similar to NAO. Overall, the annual signals are more controlled by AMO, PDO, and NAO while SOI has significant control over interannual (5-7) signals. The >8-yr signals are significantly controlled by all indices, particularly SOI. AMO and both NAO and SOI have a relatively anti-phase interrelationship with aquifer storage at annual and interannual periods, respectively while PDO's relationship seems to be relatively positive. These phase relationships roughly agree with those presented by Rezaei (2020b) for Iran's droughts.

AMO and PDO are the most controlling indices at the annual and interdecadal (>8-yr) signals in group G4 (aquifer 4) where AMO shows an anti-phase correlation while PDO has an in-phase coherence with groundwater in both the annual and interdecadal periods. NAO's significant coherence patterns are observed in the annual periods while SOI's significant coherence patterns are

related to 2-4-yr periodicities with roughly the anti-phase relationship, particularly after 2002. Overall, it seems that in group G4, SOI is the main controlling factor for interannual signals while both the AMO and PDO are the primary factors controlling the annual and interdecadal signals.

The WTCs results for group G5 show there are generally five frequency bands for which some moderate coherence patterns exist between groundwater and indices, particularly for PDO and SOI: annual (1-yr), interannual (both 2-3.5- and 4.5-6-yr periods), and interdecadal (8-12- and >15-yr periods). The 1-yr oscillatory in groundwater levels is more controlled by AMO and PDO, the 2-3.5-yr oscillatory periods by SOI and AMO, both the 4.5-6-yr and 8-12-yr periodicities by PDO, NAO, and SOI, and finally the >15-yr oscillatory by AMO and PDO. PDO has the highest effect on the interdecadal and decadal signals (i.e., 8-18-yr periods) of the groundwater (in-phase relationship). AMO largely correlates with the annual signals, particularly since 1997. SOI has moderate to strong coherence patterns that are distributed across interannual (2-4- and 5-7-yr period science 1986) and interdecadal (>10-yr) where the phase relationship is anti-phase across the 2-4-yr frequency band.

In group G6 (6a, 6b, and 6c), the moderate to strong significant coherence patterns are distributed across the three different scales of annual, interannual (2-7), and interdecadal (>8-yr). Overall, annual signals are highly correlated with AMO and to lesser magnitude PDO and NAO. The interannual signals control by all the four indices, although in 7a and 7b, SOI and PDO show the higher coherence and in 7c both NAO and AMO. NAO, SOI, and PDO respectively have higher control over interannual signals in G6. The interdecadal signals further controlled by Pacific-based indices (SOI and PDO) compared to Atlantic-based ones (AMO and NAO).

Similar to the above groups, there are several different frequency bands with significant coherence patterns: annual, interannual (4-6-yr), decadal (8-10-yr), and interdecadal (>14-yr). The annual signals in group G7 are highly controlled by AMO (particularly after 2002) and to lesser magnitude PDO and NAO. SOI, PDO, and NAO indices also highly correlated with interannual signals

(4-7-yr periods), particularly after 1990. Overall, in group G7, the decadal 8-12-yr signals are highly correlated with the Pacific-based indices of PDO and SOI rather than AMO and NAO. NAO effects on the >8-yr periods are insignificant. The interdecadal signals of >14-yr periods in aquifer 7b are highly controlled by lower-frequency indices of AMO and PDO.

WTCs from group G8 demonstrate that the annual, interannual (2-3.5- and 4-7-yr period), and decadal (>8-yr). The annual and 2-3.5-yr signals are more coherence with AMO although the other three indices may show some coherence patterns, particularly before 2000 and after 2010. The interannual 4-7-yr signals of the groundwater levels are highly correlated with PDO and SOI, particularly in aquifer 8a. The decadal signals (8-9-yr) are more controlled by PDO, SOI, and NAO.

Group G9 (aquifers 9a to 9c) shows three significant coherence patters at frequency bands of annual, interannual (5-7-yr), and decadal (>8-yr). owing to the lack of data length, the interannual signal coherence is not captured. The annual is more controlled by AMO and NAO, particularly in 9b and after 1998. About the interannual signals, the patterns are complicated where in aquifer 7a, both PDO and SOI are more important while for aquifer 7c, NAO has the highest effect on interannual signals. These complicated patterns are possibly due to that the aquifers in this group are of arid climate and deeper water tables, so that, higher attenuation and delay through unsaturated zones. However, PDO and SOI have the highest effects on the decadal signals (>9-yr).

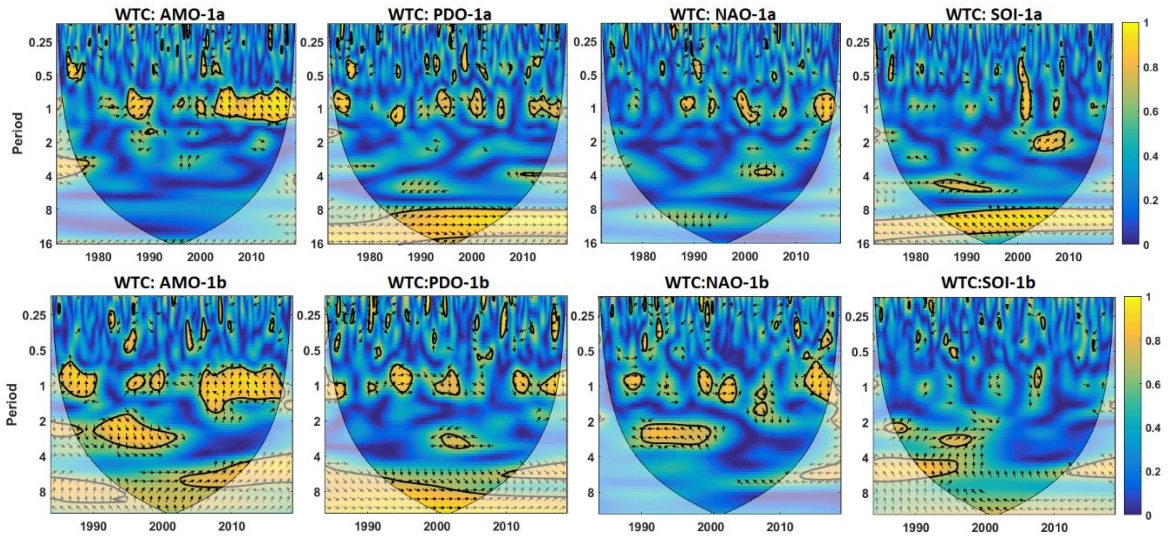
In group G10, aquifer 10a is the deepest aquifer that unlike the other aquifers, its annual coherence patterns are less. Aquifer 10b has more significant annual coherence patterns that are highly controlled by AMO. In aquifer 10a, the PDO and SOI have the highest control on both the interannual and interdecadal signals. The decadal signals of the aquifer 10b also have the highest and similar coherence patterns with both PDO and SOI.

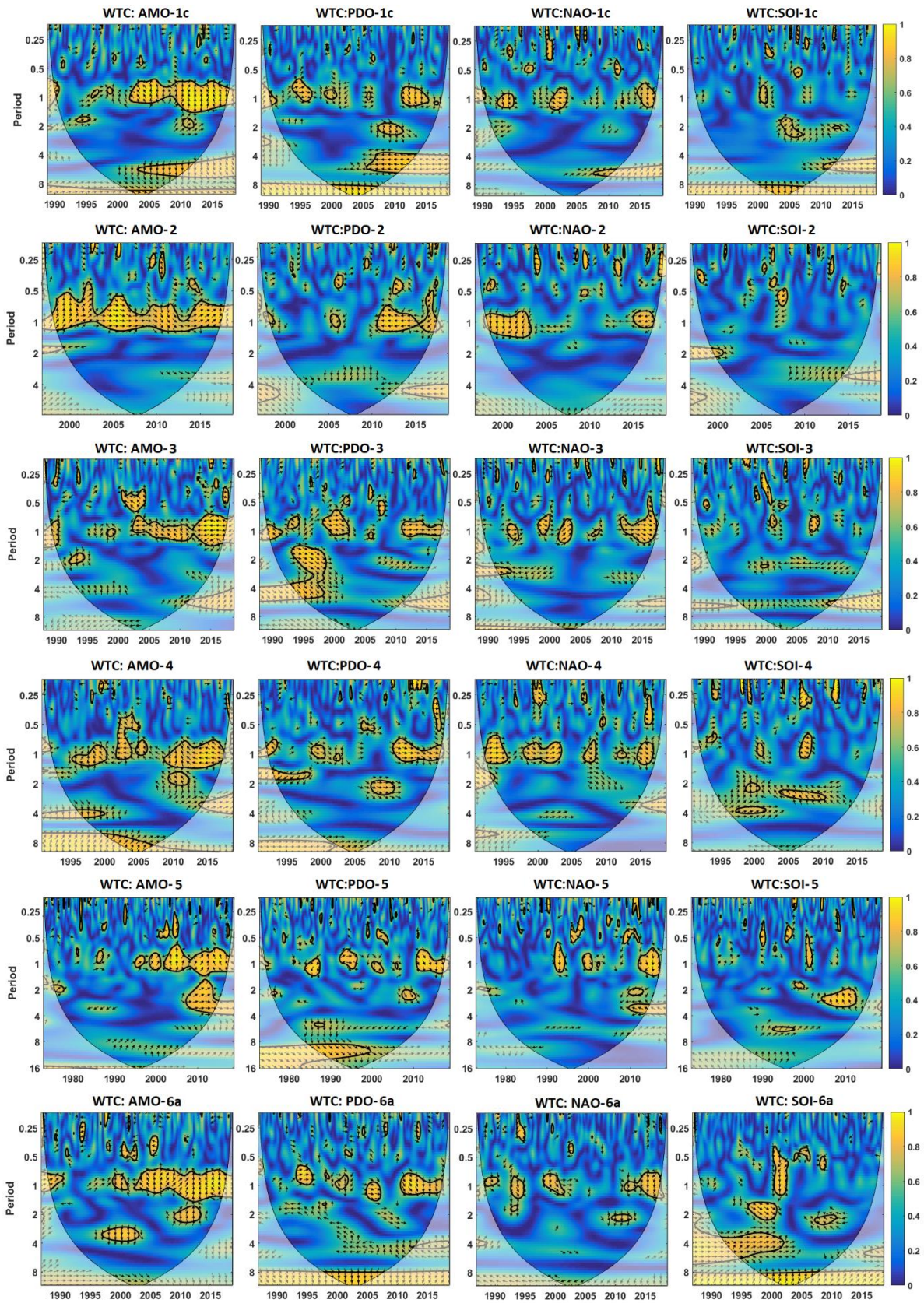
In group G11, AMO highly correlated with the annual signals while AMO and NAO have the highest effect on ~4-yr periods. Both PDO and SOI show the same significant coherence patterns at >-8yr periods before 2005 and at >4-yr after 2005.

The annual signals for group G12 are more controlled by AMO while the decadal are more affected by PDO and SOI. The interannual signals (4-6-yr) are controlled by AMO, SOI, and NAO, particularly after 2005. The interannual signals (4-8-yr) are more correlated with AMO, PDO, and SOI. Group G12 doesn't have significant interdecadal signal patterns.

In group G13, there are three scales with significant coherence patterns: annual (1-yr), 2-3.5-yr, and 5-6-yr. Owing to the lack of data length, the frequency bands of >6-yr are not captured here. However, the annual signals are more controlled by AMO and PDO similar to most aquifers while the 2-3.5-yr oscillatory is more correlated with SOI and to lesser magnitude PDO and AMO. All the four indices show significant coherence with >5-yr periods.

For aquifer 14 (i.e., G14), the most significant coherence patterns have occurred at the interannual (2-4-yr) signals that are highly correlated with SOI and PDO. The >6-yr frequency bands are not captured here due to the lack of data length.

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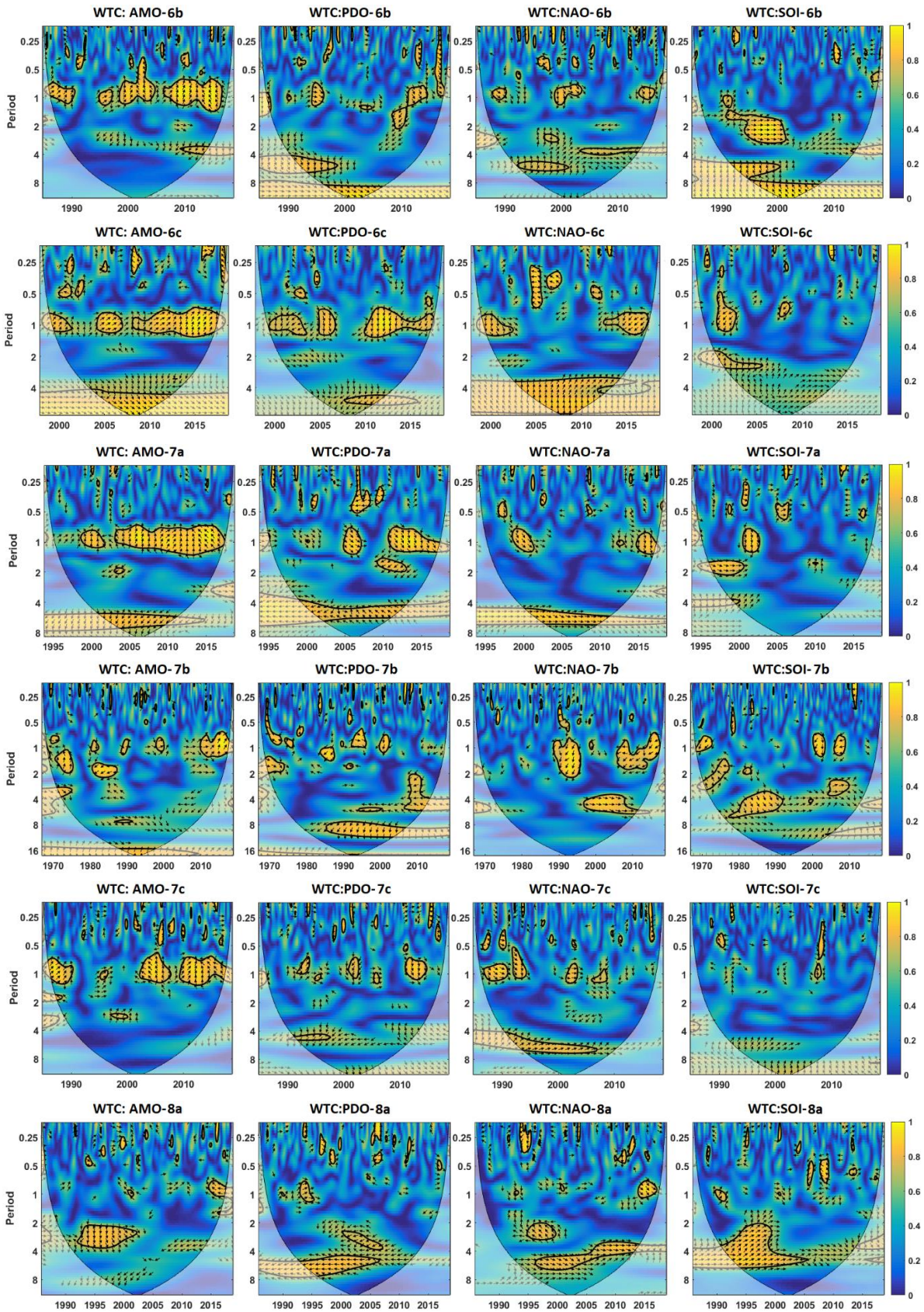
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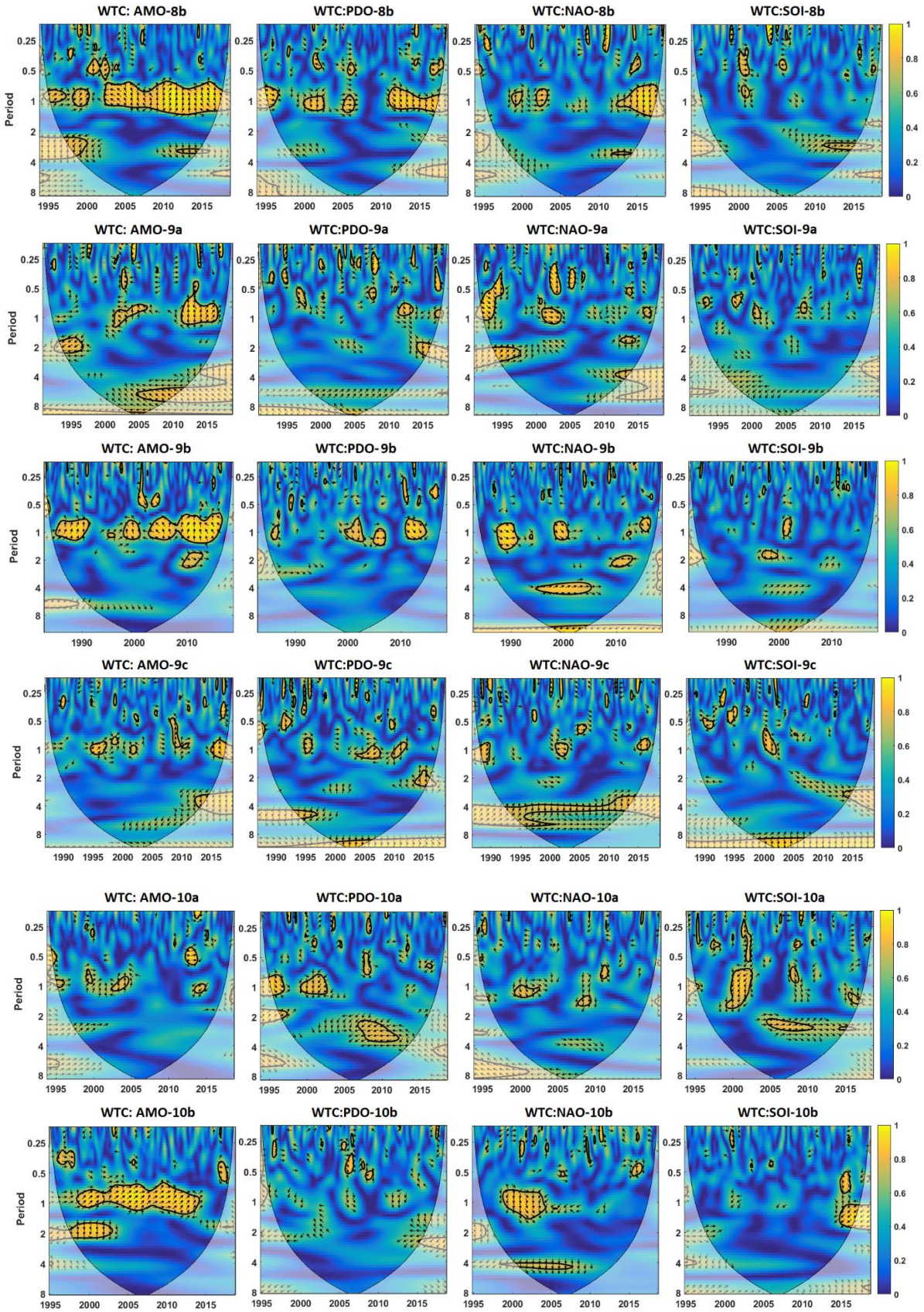
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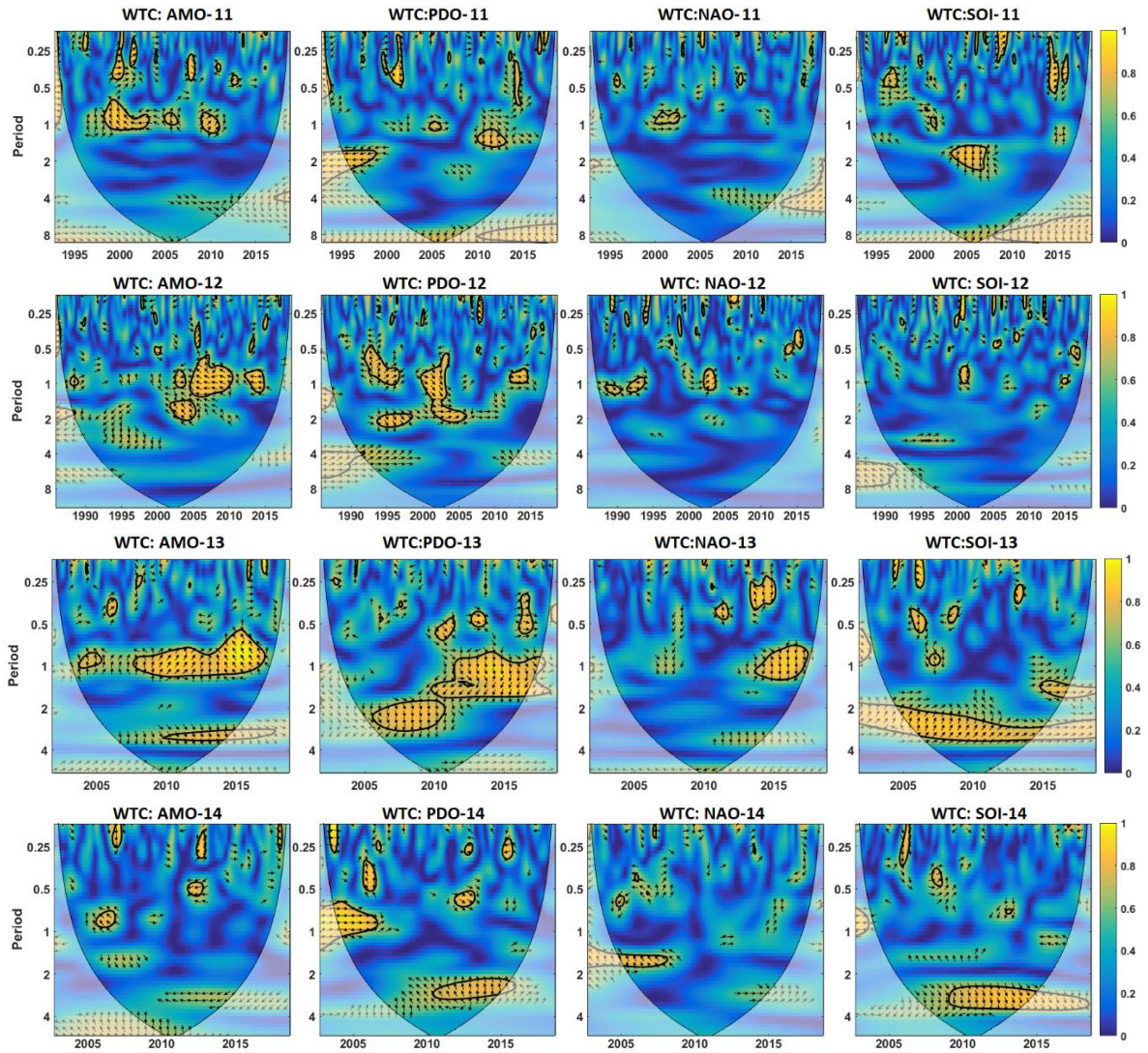

Fig. S3. The 96 WTC's runs computed for teleconnections between 24 aquifers and four climate indices of AMO, PDO, NAO, and SOI.

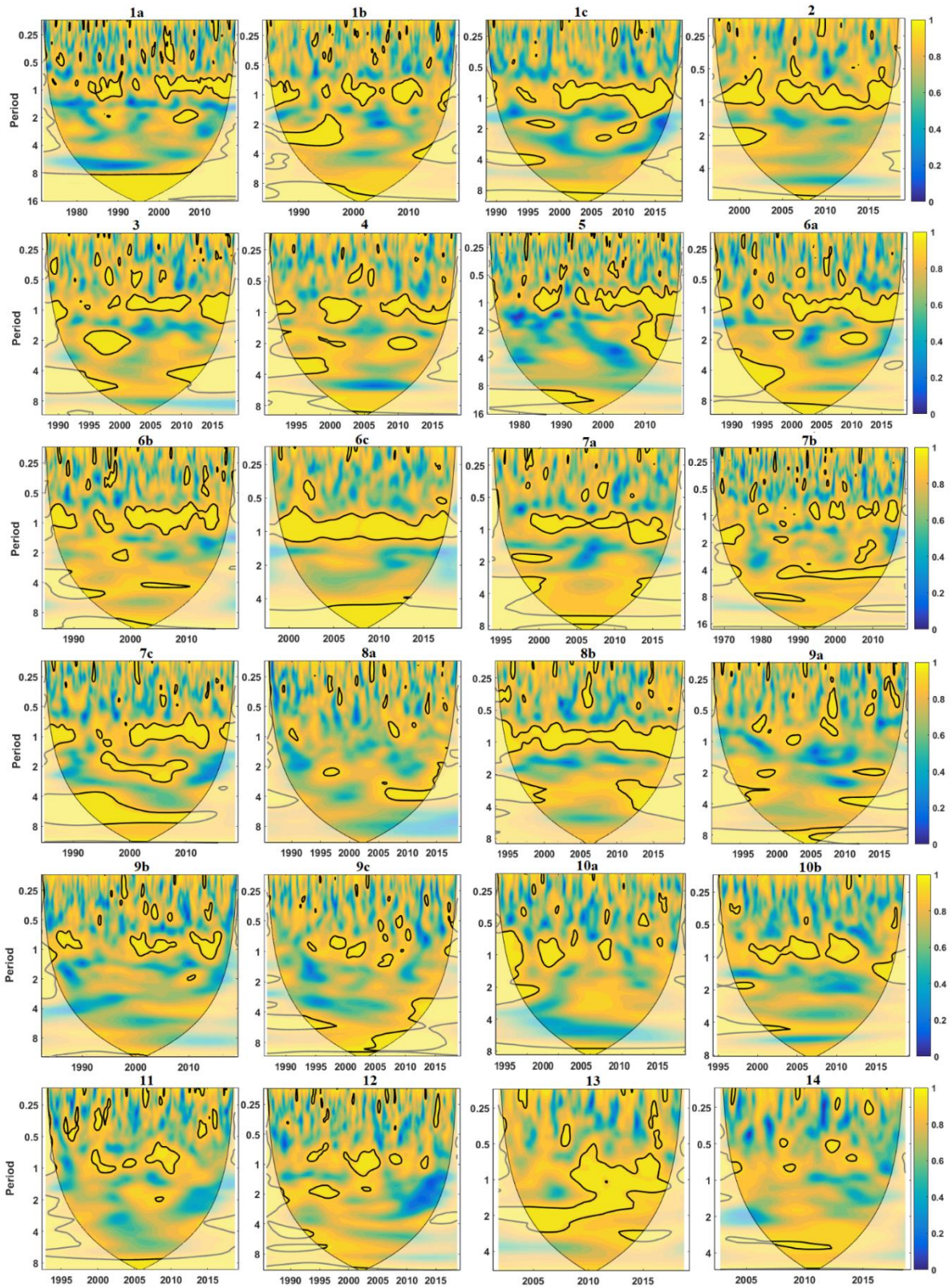

Fig. S4. The MWTCs between three-coupled AMO+PDO+SOI index and groundwater levels from all the 24 aquifers.